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MEASUREMENT OF THE  $WW\gamma$  and  $WWZ$  COUPLINGS

## AT LEP200: THE BENEFITS OF HIGHER ENERGY?

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We performed a detailed analysis of the process  $e^+e^- \rightarrow \ell\nu q\bar{q}'$  to determine its sensitivity to anomalous trilinear gauge boson couplings of the  $WW\gamma$  and  $WWZ$  vertices and how the sensitivity varies with energy and integrated luminosity. We included all tree level Feynman diagrams that contribute to this final state and used a maximum likelihood analysis of a five dimensional differential cross-section based on the  $W$  and  $W$  decay product angular distributions. For constant luminosity, increasing  $\sqrt{s}$  from 175 GeV to 192 GeV (220 GeV) improves the measurement sensitivity by a factor of 1.5 to 2 (2 to 3) depending on the parameter measured. However, the lower luminosity expected at higher  $\sqrt{s}$  will reduce these improvements. In any case, the sensitivities for  $\sqrt{s}=175$  GeV and  $L=500$  pb $^{-1}$  of  $\delta g_1^Z = \pm 0.22$ ,  $\delta\kappa_Z = \pm 0.20$ ,  $\delta\kappa_\gamma = \pm 0.27$ ,  $\delta L_{9L} = \pm 55$ , and  $\delta L_{9R} = {}^{+330}_{-230}$  are likely to be at least an order of magnitude too big to see the effects of new physics.

## I. INTRODUCTION

$e^+e^-$  colliders have contributed greatly to our knowledge of electroweak interactions [1] and it is expected that this tradition will continue in the future with the commissioning of the CERN LEP-200  $e^+e^-$  collider. One of the primary physics goals of LEP-200 is to make precision measurements of  $W$  boson properties including precision measurements of the  $W$  mass, width, and  $W$ -boson couplings with fermions and the photon and  $Z^0$ .

The latter measurements, that of the trilinear gauge boson vertices (TGV's) provides a stringent test of the gauge structure of the standard model [2]. The current measurement of these couplings are rather weak. Using a popular parametrization of the CP conserving gauge boson couplings, indirect measurements of TGV's via radiative corrections to precision electroweak measurements [3–5] give the following limits [3]:  $\delta g_1^Z = -0.033 \pm 0.031$ ,  $\delta \kappa_\gamma = 0.056 \pm 0.056$ ,  $\delta \kappa_Z = -0.0019 \pm 0.044$ ,  $\lambda_\gamma = -0.036 \pm 0.034$ , and  $\lambda_Z = 0.049 \pm 0.045$ . However, there are ambiguities in these calculations so that these limits are not particularly rigorous and it is necessary to use unambiguous direct measurements for more reliable bounds. The CDF and D0 collaborations at the Tevatron  $p\bar{p}$  collider at Fermilab, using the processes  $p\bar{p} \rightarrow W\gamma$ ,  $WW$ ,  $WZ$  have obtained the direct 95 % C.L. limits of  $-1.6 < \delta \kappa_\gamma < 1.8$ ,  $-0.6 < \lambda_\gamma < 0.6$ ,  $-8.6 < \delta \kappa_Z < 9.0$ , and  $-1.7 < \lambda_Z < 1.7$  [6]. These measurements are still quite weak but it is expected that they will improve as the luminosity of the Tevatron increases.

At LEP200 the gauge boson self-interactions will be measured in  $W$ -pair production, [2,7–13]. One of the most useful of the  $e^+e^- \rightarrow W^+W^-$  channels is  $e^+e^- \rightarrow \ell\nu q\bar{q}'$ . With only one unobserved neutrino this channel has the advantage that it can be fully reconstructed using the constraint of the initial beam energies without problems discriminating the  $W^+$  and  $W^-$  and the QCD backgrounds that plague the fully hadronic decay modes and offers much higher statistics than the fully leptonic modes [13]. As a result of its importance there have been numerous studies of this process including electroweak radiative corrections to these reactions and the important question of initial state radiation and the sensitivity of these

processes to anomalous  $WW\gamma$  and  $WWZ^0$  gauge boson couplings (TGV's) [2,7–12,14–20].

An important question for LEP200 is the sensitivity of the TGV measurements to the centre of mass energy and luminosity [21]. In this letter we study the sensitivity of the four fermion final state  $e^+e^- \rightarrow \ell\nu_\ell q\bar{q}'$  where  $\ell$  is either  $e^\pm$  or  $\mu^\pm$  and  $q\bar{q}'$  can be either  $(ud)$  or  $(cs)$  to TGV's for the centre of mass energies appropriate to LEP200,  $\sqrt{s} = 175, 192, 205$ , and  $220$  GeV, for various integrated luminosities. Our goal is to determine how the measurements will be affected by changing the center of mass energy and luminosity.

This issue has been addressed in a number of papers. The classic paper by Hagiwara, Peccei, Zeppenfeld, and Hikasa, [7] examined the sensitivity of anomalous TGV's to the process  $e^+e^- \rightarrow W^+W^-$  and how the sensitivity varied with centre of mass energies relevant to LEP200. Although this paper did point out the importance of separating longitudinally polarized  $W$ 's from transversely polarized  $W$ 's the analysis was restricted to specific angular distributions and specific  $W$  boson polarizations and varied only one parameter at a time. In addition it did not include the contributions from the so-called background contributions; other tree level diagrams that contribute to the same four fermion final state.

The information about the outgoing  $W$  polarizations can be taken into account by using the angular distributions of the  $W$  boson decay products. Sekulin [10] and Aihara *et al* [2] included this information by using a binned maximum log likelihood fit to a five dimensional differential cross section with respect to the  $W$  scattering angle and the polar and azimuthal decay angles of the  $W^+$  and  $W^-$  bosons. Both of these analysis looked at different center of mass energies relevant to LEP200 but neither included the background contributions. The analysis of Sekulin assumed the narrow width approximation for the  $W$  decays. The analysis by Aihara *et al* was more sophisticated and included initial state radiation, detector smearing, and various kinematic cuts introduced to reduce backgrounds. Aihara *et al* also assumed relations among the parameters which in the language of the non-linearly realized Chiral Lagrangian takes  $L_{9L} = L_{9R}$ . Their general conclusion that the sensitivity to the TGV parameters increased by a factor of 1.5 going from 176 GeV to 190 GeV is consistent with what we find.

The recent studies by Berends and van Sighem [12] and by Papadopoulos [11] are the closest in spirit to ours. Both of these studies included full tree level background processes and finite width effects. Berends and van Sighem also included initial state radiation but did not consider the variations with center of mass energy and did not quantify the sensitivities to TGV's. Papadopoulos looked at a range of centre of mass energies but restricted his study to specific angular distributions and varied only one parameter at a time.

In this letter we tie all the various pieces of previous analysis together; we include all tree level background processes and finite width effects, we perform a binned log likelihood fit to a five dimensional differential cross section, we varied the different parameters simultaneously so that correlations between them might show up, and we varied both the center of mass energy and luminosities relevant to LEP200.

## II. THE EFFECTIVE LAGRANGIAN

We used two common parametrizations of the TGV's. The first approach describes the  $WWV$  vertices using the most general parametrization possible that respects Lorentz invariance, electromagnetic gauge invariance and  $CP$  invariance [7,22]. This approach has become the standard parametrization used in phenomenology making the comparison of the sensitivity of different measurements to the TGV's straightforward. We do not consider  $CP$  violating operators in this paper as they are tightly constrained by measurement of the neutron electron dipole moment which constrains the two  $CP$  violating parameters to  $|\tilde{\kappa}|, |\tilde{\lambda}| < \mathcal{O}(10^{-4})$  [23]. With these constraints the  $WW\gamma$  and  $WWZ$  vertices have five free independent parameters,  $g_1^Z$ ,  $\kappa_\gamma$ ,  $\kappa_Z$ ,  $\lambda_\gamma$  and  $\lambda_Z$  and is given by [7,22]:

$$\mathcal{L}_{WWV} = -ig_V \left\{ g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}) V^\nu + \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} - \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^{-\mu} V^{\nu\lambda} \right\} \quad (1)$$

where the subscript  $V$  denotes either a photon or a  $Z^0$ ,  $V^\mu$  and  $W^\mu$  represents the photon or  $Z^0$  and  $W^-$  fields respectively,  $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$  and  $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$  and  $M_W$  is the  $W$  boson mass. ( $g_1^\gamma$  is constrained by electromagnetic gauge invariance to be equal to

1.) The first two terms correspond to dimension 4 operators and the third term corresponds to a dimension 6 operator. The mass in the denominator of the dimension 6 term would correspond to the scale of new physics, typically of order 1 TeV. However, it has become the convention to use the mass of the  $W$  boson so that the  $W$  magnetic dipole and electric quadrupole can be written in a form similar to that of the muon. Nevertheless, one expects the dimension 6 operator to be suppressed with respect to the dimension 4 operators by a factor of  $M_W^2/(\Lambda = 1 \text{ TeV})^2 \simeq 10^{-2}$ . Higher dimension operators correspond to momentum dependence [24] in the form factors which are not important at LEP200 energies and will therefore not be considered. At tree level the standard model requires  $g_1^Z = \kappa_V = 1$  and  $\lambda_V = 0$ . Typically, radiative corrections from heavy particles will change  $\kappa_V$  by about 0.015 and  $\lambda_V$  by about 0.0025 [25]. Because anomalous values of the  $\lambda_V$  are expected to be suppressed relative to those of  $g_1^Z$  and  $\kappa_V$  it is extremely unlikely that interesting constraints can be placed on them at LEP200 so we will not consider them further.

The second commonly used parametrization is the Chiral Lagrangian approach [26,27]. A custodial  $SU(2)$  is assumed which is supported to high accuracy by the nearness of the  $\rho$  parameter to 1. This approach assumes that the theory has no light Higgs particles and the electroweak gauge bosons interact strongly with each other above approximately 1 TeV. This can be described by a non-linear realization of the  $SU(2) \times U(1)$  symmetry in a chiral Lagrangian formalism leading to the effective Lagrangian:

$$L = -ig \frac{L_{9L}}{16\pi^2} \text{Tr}[W^{\mu\nu} D_\mu \Sigma D_\nu \Sigma^\dagger] - ig' \frac{L_{9R}}{16\pi^2} \text{Tr}[B^{\mu\nu} D_\mu \Sigma^\dagger D_\nu \Sigma] + gg' \frac{L_{10}}{16\pi^2} \text{Tr}[\Sigma B^{\mu\nu} \Sigma^\dagger W_{\mu\nu}] \quad (2)$$

where  $W_{\mu\nu}$  and  $B_{\mu\nu}$  are the  $SU(2)$  and  $U(1)$  field strength tensors given in terms of  $W_\mu \equiv W_\mu^i \tau_i$  by

$$\begin{aligned} W_{\mu\nu} &= \frac{1}{2}(\partial_\mu W_\nu - \partial_\nu W_\mu + \frac{i}{2}g[W_\mu, W_\nu]) \\ B_{\mu\nu} &= \frac{1}{2}(\partial_\mu B_\nu - \partial_\nu B_\mu)\tau_3, \end{aligned} \quad (3)$$

$\Sigma = \exp(iw^i \tau^i/v)$ ,  $v = 246 \text{ GeV}$ ,  $w^i$  are the would-be Goldstone bosons that give the  $W$

and  $Z$  their masses via the Higgs mechanism, and the  $SU(2)_L \times U(1)_Y$  covariant derivative is given by  $D_\mu \Sigma = \partial_\mu \Sigma + \frac{1}{2}igW_\mu^i \tau^i \Sigma - \frac{1}{2}ig'B_\mu \Sigma \tau^3$ . The Feynman rules are found by going to the unitary gauge where  $\Sigma = 1$ . Note that the coefficient  $1/16\pi^2$  is often replaced with  $v^2/\Lambda^2$ .  $L_{10}$  contributes to the gauge boson self energies where it is tightly constrained to  $-1.1 \leq L_{10} \leq 1.5$  [4] so we will not consider it further. New physics contributions are expected to result in values of  $L_{9L,9R}$  of order 1 [26].

The parameters from the two Lagrangians can be mapped onto each other [26,27]:

$$\begin{aligned} g_1^Z &= 1 + \frac{e^2}{32\pi^2 s^2 c^2} (L_{9L} + \frac{2s^2}{(c^2-s^2)} L_{10}) \\ \kappa_z &= 1 + \frac{e^2}{32\pi^2 s^2 c^2} (L_{9L} c^2 - L_{9R} s^2) + \frac{4s^2 c^2}{(c^2-s^2)} L_{10} \\ \kappa_\gamma &= 1 + \frac{1}{32\pi^2} \frac{e^2}{s^2} (L_{9L} + L_{9R} - 2L_{10}) \end{aligned}$$

### III. CALCULATIONAL APPROACH

To study the process  $e^+e^- \rightarrow \ell^\pm \nu q \bar{q}'$  we included all tree level diagrams to the four fermion final states using helicity amplitude techniques [28]. The 10 diagrams contributing to the  $e^+e^- \rightarrow \mu^\pm \nu_\mu q \bar{q}'$  final state are shown in Fig. 1. The gauge boson coupling we are studying is present in diagram (1a). This, along with diagram (1b) are the diagrams responsible for real  $W$  production. For the  $e^\pm \nu_e q \bar{q}'$  final state the 10 diagrams shown in Fig. 2 must also be included with those of Fig. 1 for a total of 20 diagrams. Diagram (2a) includes a TGV. The diagrams with t-channel photon exchange make large contributions to single  $W$  production due to the pole in the photon propagator which can be used to isolate the  $WW\gamma$  vertex from the  $WWZ$  vertex.

To evaluate the cross-sections and different distributions, we used the CALKUL helicity amplitude technique [28] to obtain expressions for the matrix elements and performed the phase space integration using Monte Carlo techniques [29]. To obtain numerical results we used the values  $\alpha = 1/128$ ,  $\sin^2 \theta = 0.23$ ,  $M_Z = 91.187$  GeV,  $\Gamma_Z = 2.49$  GeV,  $M_W = 80.22$  GeV, and  $\Gamma_W = 2.08$  GeV. In our results we included two generations of quarks and took the quarks to be massless. In order to take into account finite detector acceptance we require

that the lepton and quarks are at least 10 degrees away from the beam and have at least 10 GeV energy.

In principle we should include QED radiative corrections from soft photon emission and the backgrounds due to a photon that is lost down the beam pipe [17,20]. These backgrounds are well understood and detector dependent. We assume the approach taken at LEP, that these effects can best be taken into account by the experimental collaborations. In any case, although initial state radiation must be taken into account their inclusion does not substantially effect the bounds we obtain and therefore our conclusions.

Our primary interest here is to examine the sensitivity of TGV measurements to  $\sqrt{s}$  [2,7,10,11] and to integrated luminosity. Any disruption of the delicate gauge theory cancellations leads to large changes to the standard model results. The corrections for  $W_L$  production amplitudes can be enhanced by a factor of  $(s/M_W^2)$  [7]. Because it is the longitudinal  $W$  production which is most sensitive to anomalous couplings it is crucial to disentangle the  $W_L$  from the  $W_T$  *background*. The most convenient means of doing so makes use of the angular distributions of the  $W$  decay products. We define the 5 angles:  $\Theta$ , the  $W^-$  scattering angle with respect to the initial  $e^+$  direction,  $\theta_{qq}$ , the polar decay angle of the  $q$  in the  $W^-$  rest frame using the  $W^-$  direction as the quantization axis,  $\phi_{qq}$ , the azimuthal decay angle of the  $q$  in the  $W^-$  rest frame, and  $\theta_{\ell\nu}$  and  $\phi_{\ell\nu}$  are the analogous angles for the lepton in the  $W^+$  rest frame. These angles are shown in Fig. 3. We define the azimuthal angle as the angle between the normal to the reaction plane,  $n_1 = p_e \times p_W$  and the plane defined by the  $W$  decay products,  $n_2 = p_q \times p_{\bar{q}}$ . The angular distribution in  $\theta$  peaks about  $\cos \theta = 0$  for longitudinally polarized  $W$  bosons and at forward or backward angles for transversely polarized bosons. In addition the parity violation of the  $W$  couplings distinguishes the two polarization states adding to the effectiveness of the decay as a polarimeter. Thus, the angular distributions can be used to extract information about the  $W$  boson polarizations.

To use the information contained in these angular distributions we performed a maximum likelihood analysis based on the 5 angles described above [9,10,15]. For the  $q\bar{q}$  case there is an ambiguity since we cannot tell which hadronic jet corresponds to the quark and which

to the antiquark. We therefore include both possibilities in our analysis. To impliment the maximum likelihood analysis we divided each of  $\Theta$ ,  $\theta_{qq}$ ,  $\phi_{qq}$ ,  $\theta_{\ell\nu}$ , and  $\phi_{\ell\nu}$  into four bins so that the entire phase space was divided into  $4^5 = 1024$  bins. Given the cross-section of  $\sim 1$  pb per mode with this many bins some will not be very populated with events so that it is more appropriate to use Poisson statistics rather than Gaussian statistics. This leads naturally to the maximum likelihood method. The change in the log of the Likelihood function from the standard model expectation is given by

$$\delta \ln \mathcal{L} = \sum [-r_i + r_i \ln(r_i) + \mu_i - r_i \ln(\mu_i)] \quad (4)$$

where the sum extends over all the bins and  $r_i$  and  $\mu_i$  are the predicted number of non-standard model and standard model events in bin  $i$  respectively, given by

$$r_i = L \int_{\Delta\Theta} \int_{\Delta\theta_{qq}} \int_{\Delta\phi_{qq}} \int_{\Delta\theta_{\ell\nu}} \int_{\Delta\phi_{\ell\nu}} \frac{d^5\sigma}{d \cos \Theta d \cos \theta_{qq} d \phi_{qq} d \cos \theta_{\ell\nu} d \phi_{\ell\nu}} d \cos \Theta d \cos \theta_{\ell\nu} d \phi_{\ell\nu} d \cos \theta_{qq} d \phi_{qq} \quad (5)$$

where  $L$  is the expected integrated luminosity. The 68% and 95% confidence level bounds are given by the values of anomalous couplings which give a change in  $\ln \mathcal{L}$  of 0.5 and 2.0 respectively.

The results presented here are based solely on the statistical errors based on the integrated luminosity we assume for the various cases. To include the effects of systematic errors using the maximum likelihood approach requires an unweighted Monte Carlo simulation through a realistic detector. Since we did not have the facilities to do this we attempted a simplified estimate of systematic errors using a  $\chi^2$  analysis to make our estimates. Assuming a systematic 5% measurement error combined in quadrature with the statistical error we found that the systematic errors are neglible compared to the statistical errors for the integrated luminosities anticipated at LEP200. That this is so is a consequence of the large number of bins resulting in a small number of events per bin leading to a large statistical error. Thus, it appears as if the systematic errors will be dominated by statistical errors but clearly, a full detector Monte Carlo must be performed to properly understand the situation.



## IV. RESULTS AND DISCUSSION

A thorough analysis of gauge boson couplings would allow all parameters in the Lagrangian to vary simultaneously to take into account cancellations (and correlations) among the various contributions. This approach is impractical, however, due to the large amount of computer time that would be required to search the parameter space. Instead we show 2-dimensional C.L. contours for a selection of parameter pairs to give a sense of the correlations. We believe that these contours are reasonably reliable as when the other parameters at the edges of our 2-dimensional contours were varied, there was little change in the sensitivities. For the case of the Chiral Lagrangian where the global  $SU(2)$  symmetry imposes relations between the parameters and where we restrict ourselves to dimension four operators the parameter space reduces to 2 dimensions.

For the results we present here we did not include a cut on  $M_{\ell\nu}$  or  $M_{q\bar{q}}$  as these cuts in general have virtually no effect on the sensitivities except for the electron mode involving the  $WW\gamma$  vertex where the effect is still quite small. We calculated the sensitivities of anomalous couplings for  $\sqrt{s} = 175, 192, 205$ , and  $220$  GeV assuming the same integrated luminosity of  $500 \text{ pb}^{-1}$  for all cases for the purposes of comparison. We show the sensitivities that can be obtained by combining the  $e^+$ ,  $e^-$ ,  $\mu^+$ , and  $\mu^-$  modes to improve the statistics. The 95% confidence limit contours for the  $g_1^Z - \kappa_Z$ ,  $\kappa_\gamma - \kappa_Z$ , and  $L_{9L} - L_{9R}$  planes are shown in Fig. 4. The sensitivities of the couplings, varying one parameter at a time, are summarized in Table I.

At threshold, anomalous couplings are quite sensitive to energy with improvements in sensitivities going from  $\sqrt{s} = 175$  GeV to  $\sqrt{s} = 192$  GeV ranging from about 1.7 for  $\kappa_Z$  to  $\sim 2$  for  $L_{9R}$ . The corresponding changes going from  $\sqrt{s} = 205$  GeV to  $\sqrt{s} = 220$  GeV are 1.2 for  $\kappa_Z$  and  $\sim 1.4$  for  $L_{9R}$ . This occurs even though the cross section only varies from 1.10 pb (1.15 pb) at 175 GeV to its maximum value of 1.28 pb (1.31 pb) at 200 GeV for the  $\mu$  ( $e$ ) mode. We included the angular cuts but not the energy cuts on the final state fermions to obtain these numbers.

The sensitivity can be understood by examining the helicity amplitudes in detail which are given by Hagiwara *et al.* in Ref. [7]. At threshold the  $\nu$ -exchange diagram dominates so that at low energy the  $\gamma$  and  $Z$  diagrams are down by a factor of  $\beta = \sqrt{1 - 4M_W^2/s}$  compared to the  $\nu$ -exchange diagram. Thus, at threshold the cancellation between the various diagrams are less important than at higher energies. Near threshold the contributions from anomalous couplings go roughly like  $\beta$  with a further enhancement of roughly  $\sqrt{s}/2M_W$  for each longitudinal  $W$  boson in the final state. The net results is that in the threshold region the reaction  $e^+e^- \rightarrow W^+W^-$  is not very sensitive to the 3-vector boson coupling.

The improvement in sensitivities going to higher energies is slightly misleading as we have assumed that the luminosities would be the same in all cases. In reality one expects that the luminosities will be lower for the higher energies [21]. The coupling measurements are limited by statistics which are in turn related to the number of events so that the sensitivities are inversely proportional to the square root of the integrated luminosity;  $\delta \propto L^{-1/2}$ . Reducing the luminosity from  $500 \text{ pb}^{-1}$  to  $300 \text{ pb}^{-1}$  decreases the sensitivity by a factor of 1.3 which limits the usefulness of increasing the center of mass energy.

In any case, these limits are at the very least an order of magnitude less sensitive than would be required to see the effects of new physics through radiative corrections and are comparable to the sensitivities that could be achieved at a high luminosity Tevatron upgrade. It is therefore unlikely, that new physics will reveal itself at LEP200 through precision measurements of the TGV's.

## V. CONCLUSIONS

The primary purpose of this note was to examine the sensitivity of anomalous gauge boson coupling measurements at LEP200 to changes in the center of mass energy. As  $W$  pair production is relatively insensitive to TGV's near threshold a modest increase in energy from  $\sqrt{s} = 175 \text{ GeV}$  to  $192 \text{ GeV}$  could yield sizable improvements in the measurements. Subsequent increases in energy to  $205 \text{ GeV}$  and  $220 \text{ GeV}$  would not yield the same improve-

ment. However, this statement must be tempered with the reality that increases in energy would likely result in lower luminosities and statistics with the corresponding measurement degradation.

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## FIGURES

FIG. 1. The Feynman diagrams contributing to the process  $e^+e^- \rightarrow \mu^+\nu_\mu q\bar{q}'$ .

FIG. 2. The Feynman diagrams that contribute to the process  $e^+e^- \rightarrow e^+\nu_\mu q\bar{q}'$  in addition to those of fig 1.

FIG. 3. Angle definitions used in our analysis.  $\Theta$  is the  $W$  scattering angle,  $\theta_{qq}$  and  $\theta_{\ell\nu}$  are the decay angles in the  $W$  rest frame and  $\phi_{qq}$  and  $\phi_{\ell\nu}$  are the azimuthal angles, again the  $W$  rest frames.

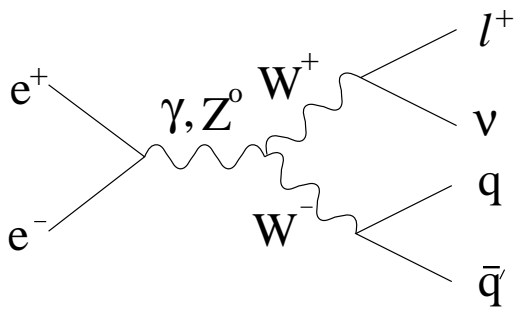
FIG. 4. 95% C.L. contours for sensitivity to anomalous couplings for  $\sqrt{s} = 175, 192, 205$ , and 220 GeV. In all cases the contours are obtained from combining all 4 lepton charge states for  $L=500 \text{ pb}^{-1}$ . The contours correspond to increasing energy going from the outer contour to the inner with the outermost contour corresponding to  $\sqrt{s} = 175 \text{ GeV}$  and the innermost corresponding to  $\sqrt{s} = 220 \text{ GeV}$ .

# TABLES

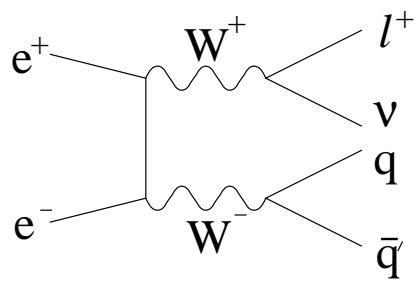
TABLE I. Sensitivities to anomalous couplings for the various parameters varying one parameter at a time. The values are obtained by combining the four lepton modes ( $e^-$ ,  $e^+$ ,  $\mu^-$ , and  $\mu^+$ ) and two generations of light quarks ( $ud$ ,  $cs$ ). The results are 95% confidence level limits for the given integrated luminosities.

| $\sqrt{s}$<br>(GeV) | L<br>(pb $^{-1}$ ) | $g_1^Z$            | $\kappa_Z$         | $\kappa_\gamma$    | $L_{9L}$       | $L_{9R}$         |
|---------------------|--------------------|--------------------|--------------------|--------------------|----------------|------------------|
| 175                 | 500                | $\pm 0.22$         | $+0.19$<br>$-0.20$ | $+0.27$<br>$-0.26$ | $\pm 55$       | $+330$<br>$-230$ |
| 175                 | 300                | $+0.28$<br>$-0.29$ | $\pm 0.25$         | $+0.36$<br>$-0.33$ | $\pm 70$       | $+440$<br>$-300$ |
| 192                 | 500                | $\pm 0.15$         | $\pm 0.12$         | $+0.16$<br>$-0.14$ | $+35$<br>$-34$ | $+170$<br>$-120$ |
| 192                 | 300                | $\pm 0.20$         | $\pm 0.16$         | $+0.21$<br>$-0.18$ | $+46$<br>$-44$ | $+240$<br>$-150$ |
| 205                 | 500                | $\pm 0.14$         | $\pm 0.11$         | $+0.12$<br>$-0.11$ | $+31$<br>$-29$ | $+120$<br>$-100$ |
| 205                 | 300                | $\pm 0.18$         | $\pm 0.13$         | $+0.17$<br>$-0.14$ | $+40$<br>$-38$ | $+190$<br>$-110$ |
| 220                 | 500                | $+0.10$<br>$-0.08$ | $\pm 0.09$         | $+0.10$<br>$-0.08$ | $+28$<br>$-26$ | $+100$<br>$-60$  |
| 220                 | 300                | $+0.13$<br>$-0.12$ | $\pm 0.12$         | $+0.13$<br>$-0.10$ | $+36$<br>$-33$ | $+135$<br>$-90$  |

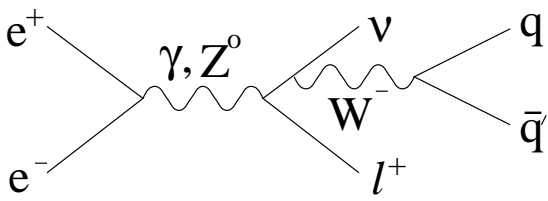




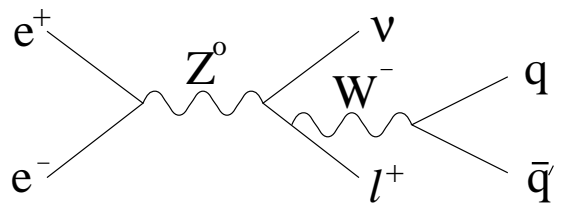
(a)



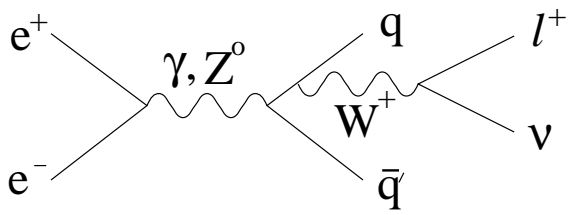
(b)



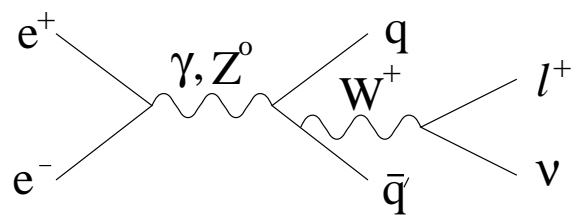
(c)



(d)



(e)



(f)

